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Performance Report for ONR Grant N00014-94-1-0284 Distributed Methods for Controlling Multiple Mobile Robots

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1 Brief Summary

This project is supported jointly by ONR Grant N00014-94-1-0284 and NSF Grant IRI-9307506. Although the official starting date of the ONR grant was November 1, 1993, the work started when the NSF grant arrived in August 1993. So in the following, we report the activities since August 1993. However, since UWM received the official notification and the ONR grant number in late January, 1994, we were not able to acknowledge the support from ONR in some of the articles mentioned in this report.

The intent of the project is to study the fundamentals of the distributed control method for multiple mobile robots and develop a theory for applying the method effectively. In this method, at every tick of its local clock, each robot observes the positions of all the robots and moves to a new position determined by the given algorithm. Typically, we assume that the robots are anonymous (they all execute the same algorithm and they cannot be distinguished by their appearances), initially they do not have a common x-y coordinate system, and their local clocks may not be synchronized. A basic problem for such a robot system is to design an algorithm that, when executed individually by the robots, allows the robots as a group to achieve the given goal.

During the first year of the project, two major topics were addressed: (1) theoretical investigation of the power and limitations of the distributed method, and (2) development of robot algorithms under realistic assumptions. These topics are summarized in the next two subsections.

1.1 Power and limitations of the distributed method

For the first topic, we discussed a number of problems related to the formation of various geometric figures in the plane by the robots. The problems include (a) convergence to a single point, (b) moving the robots to a single point in finite steps, (c) agreement on a single point, (d) agreement on the unit distance, (e) agreement on direction, and (f) leader election. Specifically, we obtained an oblivious (i.e., memoryless) algorithm for Problem (a), and discussed the subtlety of the problem by showing how certain minor changes in the algorithm affect the possibility of achieving the goal. We then showed that Problem (b) can be solved by a nonoblivious algorithm but not by any oblivious algorithm. This result reveals a limitation of oblivious algorithms. Problems (c), (d) and (e) together constitute the problem of agreeing on a common x-y coordinate system. We developed nonoblivious algorithms for solving Problems (c) and (d), and showed that Problem (e) is not solvable even if there are only two robots and their clocks are synchronized. This result shows that the robots cannot agree on a common x-y coordinate system in general. But if the robots have a sense of direction, then the robots can agree on a common x-y coordinate system and elect a leader (Problem (f)), provided that no "clones" exist. Also, we showed that the set of geometric figures realizable by any deterministic algorithm includes the configuration in which all robots are located at the same position. This reveals a

limitation of deterministic algorithms.

In addition, recently we obtained a characterization of the class of geometric figures that can be formed when the local clocks of the robots are synchronized. We found that whether or not any particular geometric figure can be formed depends not only on the initial distribution of the robots, but also on their local x-y coordinate systems.

The work summarized above has resulted in articles 2 and 7 in the list given at the end of this report. Article 7 will soon be submitted for journal publication.

1.2 Algorithms under realistic assumptions

The theoretical results mentioned above were obtained under the assumption that a robot is a point. This assumption helped us to discover some of the fundamental properties of the distributed control method. For the second topic, we considered more realistic constraints, such as the size of a robot and sensor errors. Specifically, we modified some of the algorithms developed previously, assuming that each robot is a disc. We developed a simple collision avoidance strategy for the robots, and used it in the simulation of all the robot algorithms we developed. The algorithms performed well in simulation when executed with the strategy. We also simulated sensor and control errors.

Also, under the same assumption we developed algorithms for moving the robots through a narrow gate. Congestion resolution was found to be a major issue for this problem. Simulation results indicate that the overall performance of the system can change if different congestion resolution strategies are used.

The work summarized above has resulted in articles 3 and 5. We are currently working on an extension of the results in article 3 to motion coordination in a 3D space. The reluts may be applied to distributed traffic control of robots.

1.3 Related projects

In addition, we worked on three projects peripherally related to this research.

One is on the formal verification of systems consisting of many identical processes. (A collection of robots can be viewed as such a system.) We considered systems in which the components are connected as a ring, and developed some "structural induction theorems" that can be used to infer the correctness of any large ring from the correctness of rings having fewer components. Experience in this work might help us in the future in the analysis of robot algorithms. This work has resulted in article 9.

The second is on the development of efficient algorithms in computational geometry. As is the case with many geometric algorithms, the algorithms we developed might be applicable in certain robotics applications. This work has resulted in articles 1, 4 and 10.

The third project is a study of efficient algorithms on a parallel machine having a mesh structure. Experiences with such machines might help us later if we do parallel

simulation of multi-robot systems. This work has resulted in articles 6 and 8.

2 Work to be Performed During the Succeeding Period

In the second year of the project, we plan to continue to work on both theoretical questions and practical issues. One of the goals of the theory part is to give a formal analysis of some of the heuristic algorithms for forming geometric figures. (In many cases, only simulation results are provided for such algorithms.) Also, we will continue to work on the design and testing of algorithms, taking into account realistic constraints, such as the size of a robot and sensor errors.

Specifically, the work during the second year will be along the lines of the activities that are currently under way, which we summarize now. Zhengyuan Chen, a computer science graduate student with a physics background, is working on two problems. One is mathematical analysis of convergence of some of the known heuristic algorithms for mobile robots. The other problem is the development of effective algorithms for moving an object by a team of mobile robots. Kinematics of the robots will be taken into consideration in the latter work. Another computer science graduate student, Rajiv Malhotra, is working on the problem of cooperation among autonomous robots, in the context of surveillance. We are planning to investigate how communication among the robots affects their overall performance, by designing and evaluating algorithms having different levels of intentional coordination. Two other graduate students, Jianan Li and Nathan Folwell, have worked with Suzuki on the related projects explained in **1.3**. Li worked on the verification of systems consisting of many processes, and is currently working toward his Ph.D. degree. Folwell recently completed his MS thesis that discusses efficient sorting algorithms on a mesh-connected parallel machine. In addition, Yamashita supervises two graduate students who are working on related problems at Hiroshima University. One of them is developing algorithms for robots with limited visibility. Consideration of limited visibility is important for practical applications of robot algorithms. The other student works on motion coordination of mobile robots in a 3D space under realistic constraints. Finally, at UWM we plan to involve a computer science undergraduate student as a student-help in the project, in the near future.

3 Collaboration

Masafumi Yamashita of Hiroshima University visited UWM for a month in April–May, 1994, and worked on the project with Ichiro Suzuki. Yamashita and Suzuki worked on the revision of a paper for journal submission, started a work on extensions of some of the results they reported in 1993, and discussed future plans of the project. Suzuki is planning to repay the visit several times in Fall 1994, when he will stay in

Japan on sabbatical. Suzuki will visit other robotics researchers in Japan during the same period.

Suzuki attended the 1994 IEEE International Conference on Robotics and Automation, San Diego, in May 1994. Yamashita attended the 2nd International Symposium on Distributed Autonomous Robotic Systems, Wako, Japan, in July 1994.

4 Other Research Support

Ichiro Suzuki has a matching research grant from NSF, IRI-9307506 *Distributed Methods for Controlling Multiple Mobile Robots*, which is funded under the sponsorship of Dr. Howard Moraff. This is a three-year project (August 1, 1993 - July 31, 1996) at the level of $38,056, $41,055, $43,830 for the three years and $122,941 total.

5 List of Publications

1. S. Guha and I. Suzuki, "Proximity problems for points on a rectilinear plane with rectangular obstacles," submitted to *Algorithmica*, September 1993.

2. I. Suzuki and M. Yamashita, "Formation and agreement problems for anonymous mobile robots," in *Proceedings of the 31th Annual Allerton Conference on Communication, Control, and Computing*, University of Illinois, Urbana, Illinois, October 1993, pp. 93–102.

3. T. Minami, H. Kakugawa, I. Suzuki and M. Yamashita, "On motion coordination of robots with volume," in *Proceedings of the 1993 Joint Symposium on Electronics and Information*, IEICE, Hiroshima, Japan, October 1993, p. 337. A revised version is available as Technical Report 94-02-03, Department of Electrical Engineering and Computer Science, University of Wisconsin - Milwaukee, July 1994.

4. S. Guha and I. Suzuki, "Proximity problems and the Voronoi diagram on a rectilinear plane with rectangular obstacles," in *Proceedings of the 13th Conference on Foundations of Software Technology and Theoretical Computer Science*, Bombay, India, *Lecture Notes in Computer Science 761*, Springer-Verlag, December 1993, pp. 218–227.

5. K. Sugihara and I. Suzuki, "Distributed algorithms for controlling multiple mobile robots," submitted to *Journal of Robotic Systems*, January 1994.

6. N. Folwell, S. Guha and I. Suzuki, "A practical algorithm for integer sorting on mesh-connected computers," submitted to *5th Symposium on the Frontiers of Massively Parallel Computation*, May 1994.

7. I. Suzuki and M. Yamashita, "A theory of distributed anonymous mobile robots—Formation and agreement problems," Technical Report 94-07-01, Department of Electrical Engineering and Computer Science, University of Wisconsin - Milwaukee, July 1994.

8. N. Folwell, "A new algorithm for sorting on mesh-connected computers," MS Thesis, Department of Electrical Engineering and Computer Science, University of Wisconsin - Milwaukee, July 1994.

9. J. Li, I. Suzuki and M. Yamashita, "Fair Petri nets and structural induction for rings of processes," *Theoretical Computer Science*, to appear.

10. D. Crass, I. Suzuki and M. Yamashita, "Searching for a mobile intruder in a corridor—The open edge variant of the polygon search problem," *International Journal of Computational Geometry & Applications*, to appear.